



Federal Building and Fire Safety Investigation of the World Trade Center Disaster

**International Workshop on Mutual Recognition
Agreements (MRA) For Telecommunications Equipment**

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October 3, 2005

NIST WTC Investigation Objectives

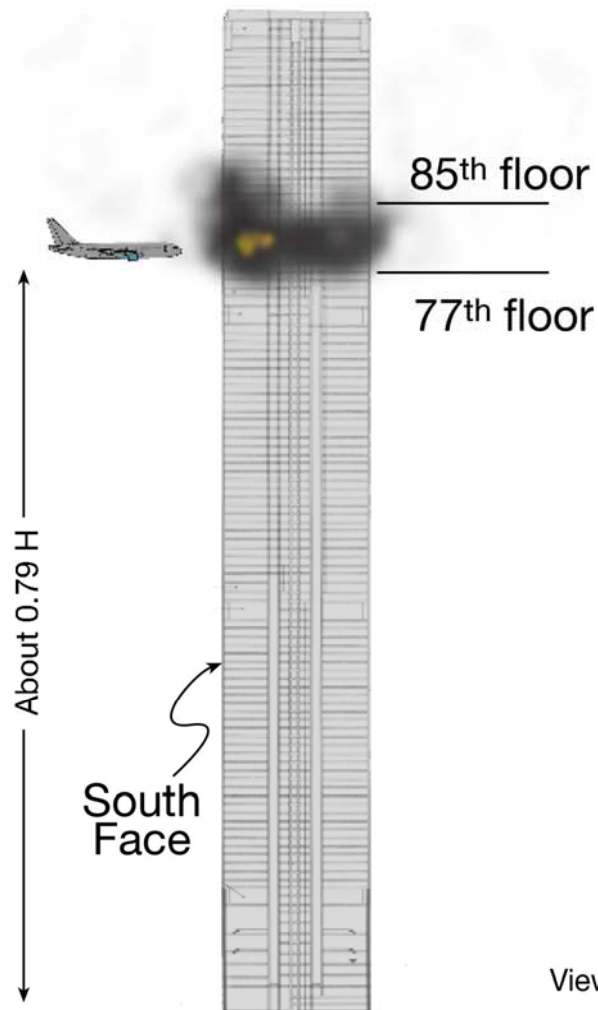
Determine:

- why and how the WTC towers collapsed following the initial impact of the aircraft, and
- why and how the 47-story WTC 7 collapsed.

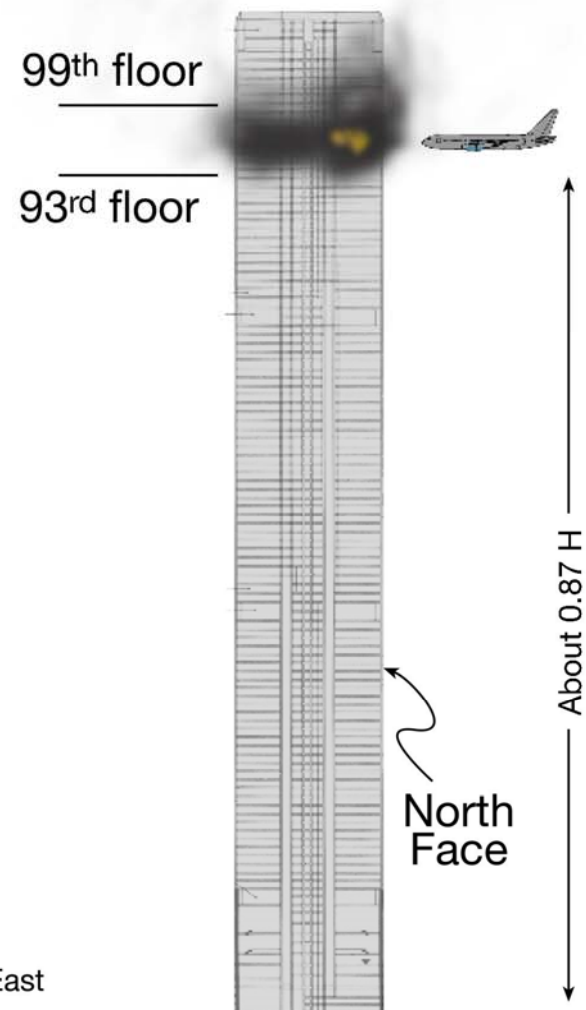
Determine why numbers of injuries and fatalities were so low or high depending on location, including technical aspects of fire protection, occupant behavior, evacuation, and emergency response.

Determine procedures and practices used in the design, construction, operation, and maintenance of the WTC buildings.

Identify specific areas in current national building and fire model codes, standards, and practices that warrant revision.



WTC 2: Hit at 9:02:59 a.m.
Collapsed after 56 minutes



WTC 1: Hit at 8:46:30 a.m.
Collapsed after 102 minutes

View from the East



Credit: NOAA
September 23, 2001

WTC Towers Design

Representative Elevation

Underground
Car Park
(total capacity 2000)

Technical Services

Skylobby

Technical Services

Skylobby

Technical Services

Express Elevators

Local
Elevators

Express
Elevators

Technical Services

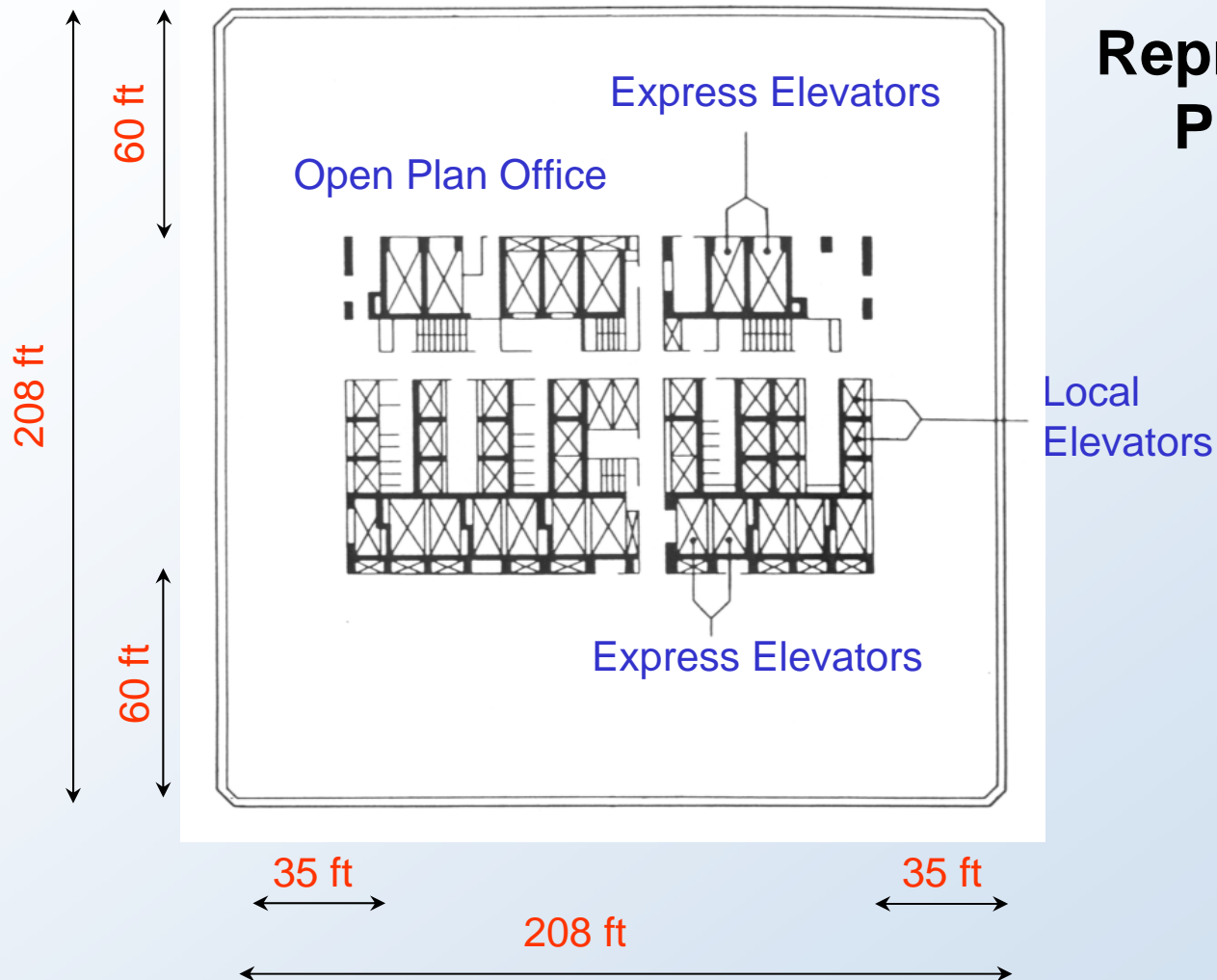
Plaza Level

Local
Elevators

110 stories = 1362 ft (North), 1368 ft (South)

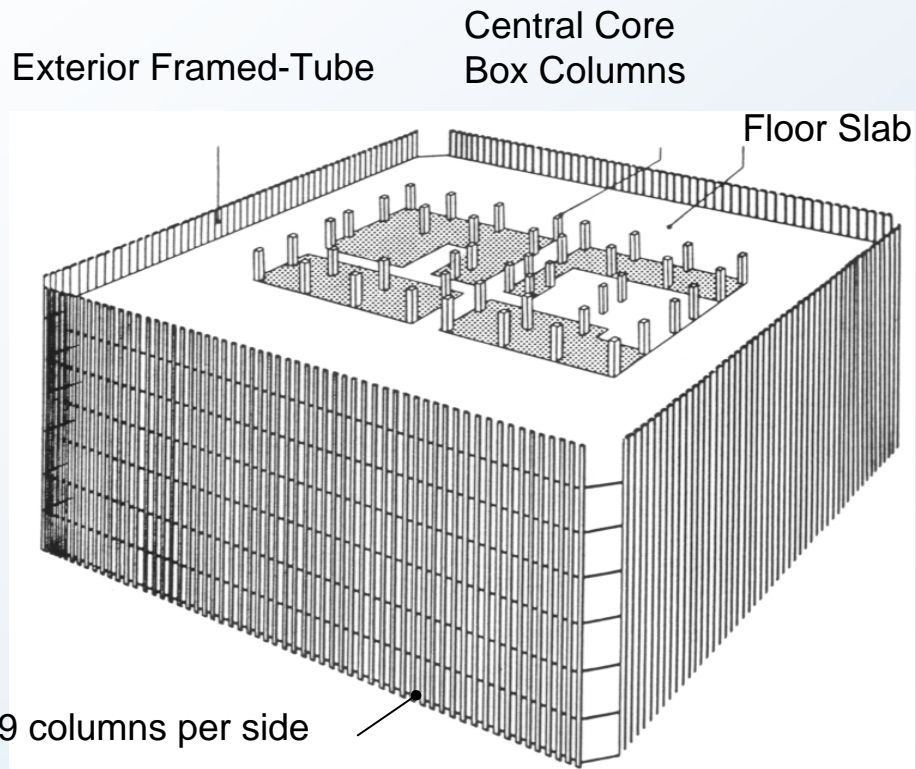
6 stories

WTC Towers Design

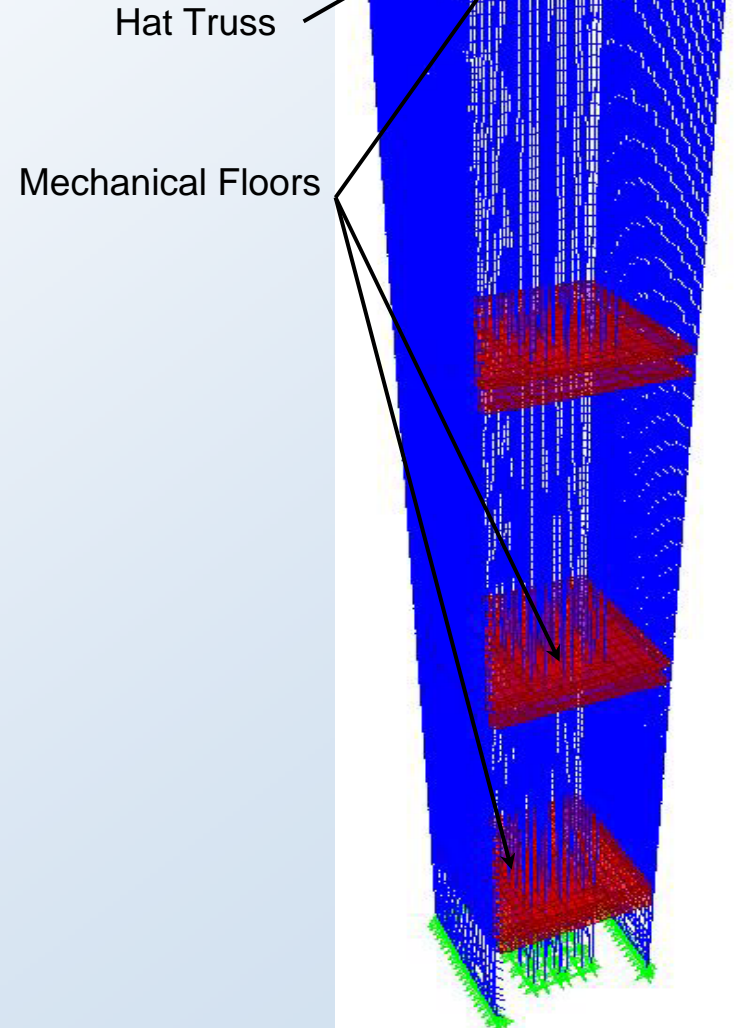


**Representative
Plan View**

WTC Towers Design

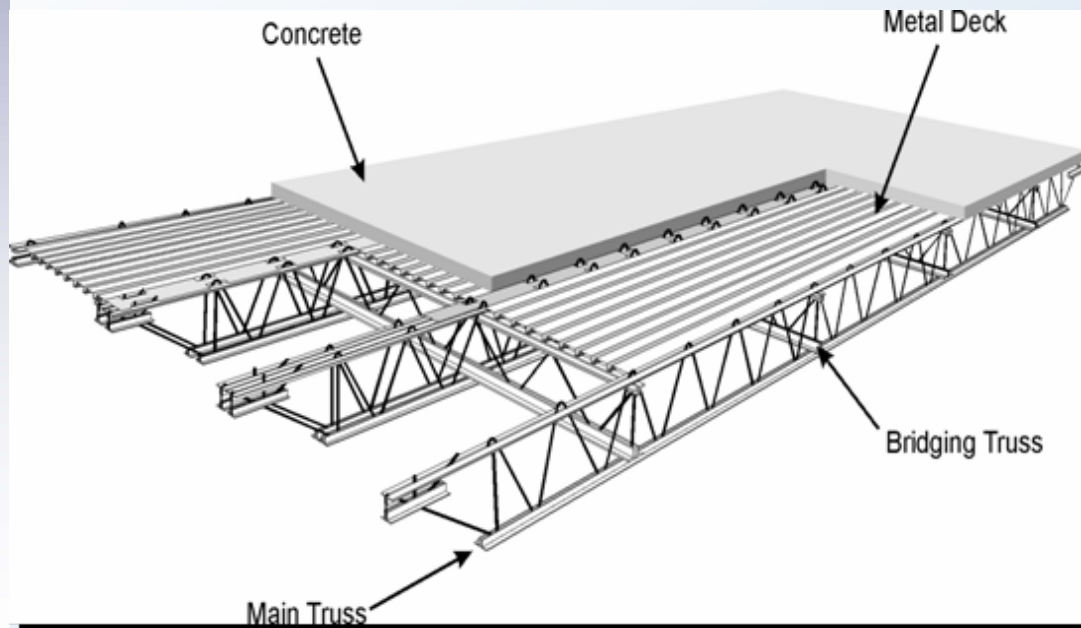


Full Building Model



WTC Towers Design

Composite floor truss system
using long span open-web bar
joists and spray-applied
fireproofing



Floors attached to
perimeter column trees

Interior Views of WTC Tower



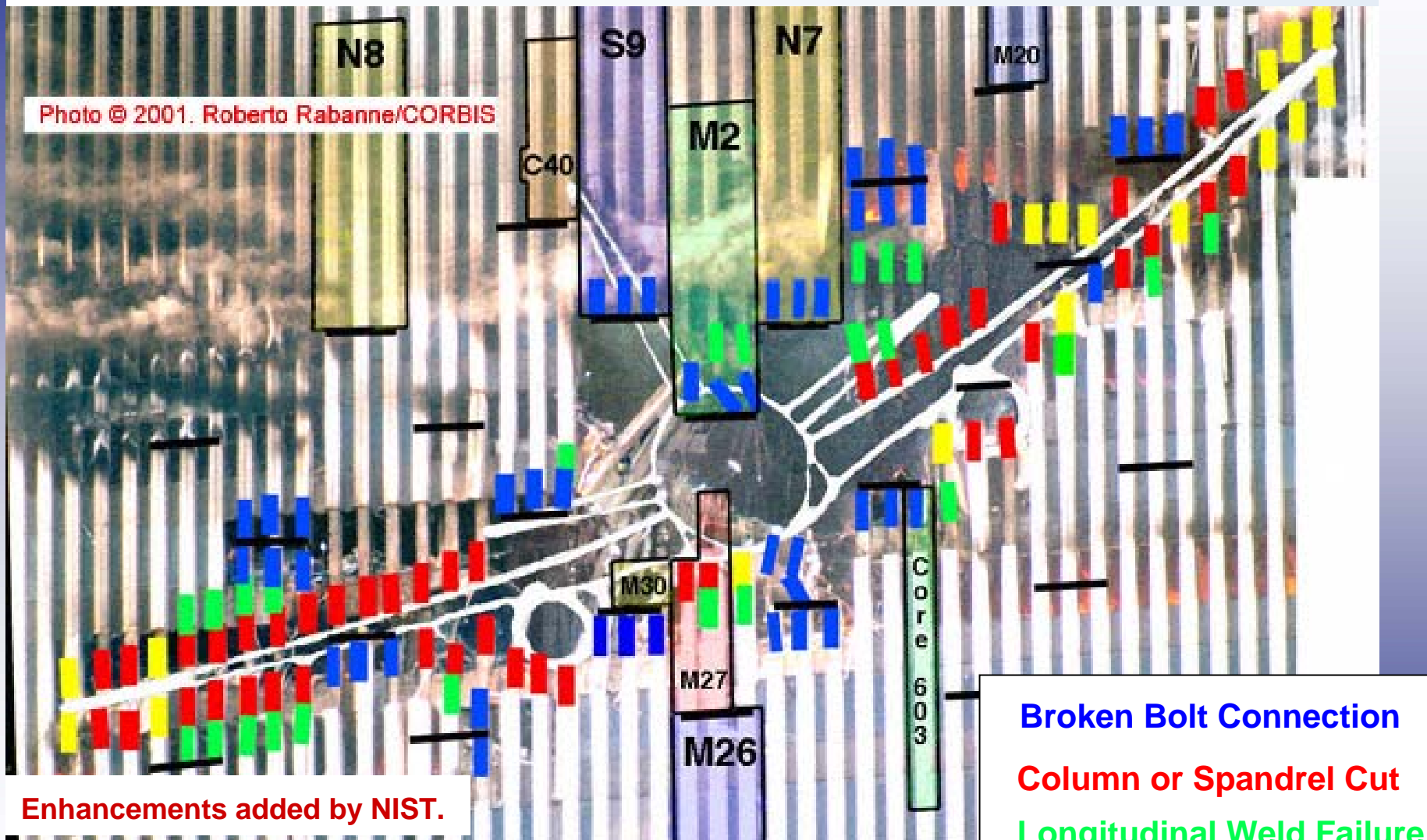
Office Floor



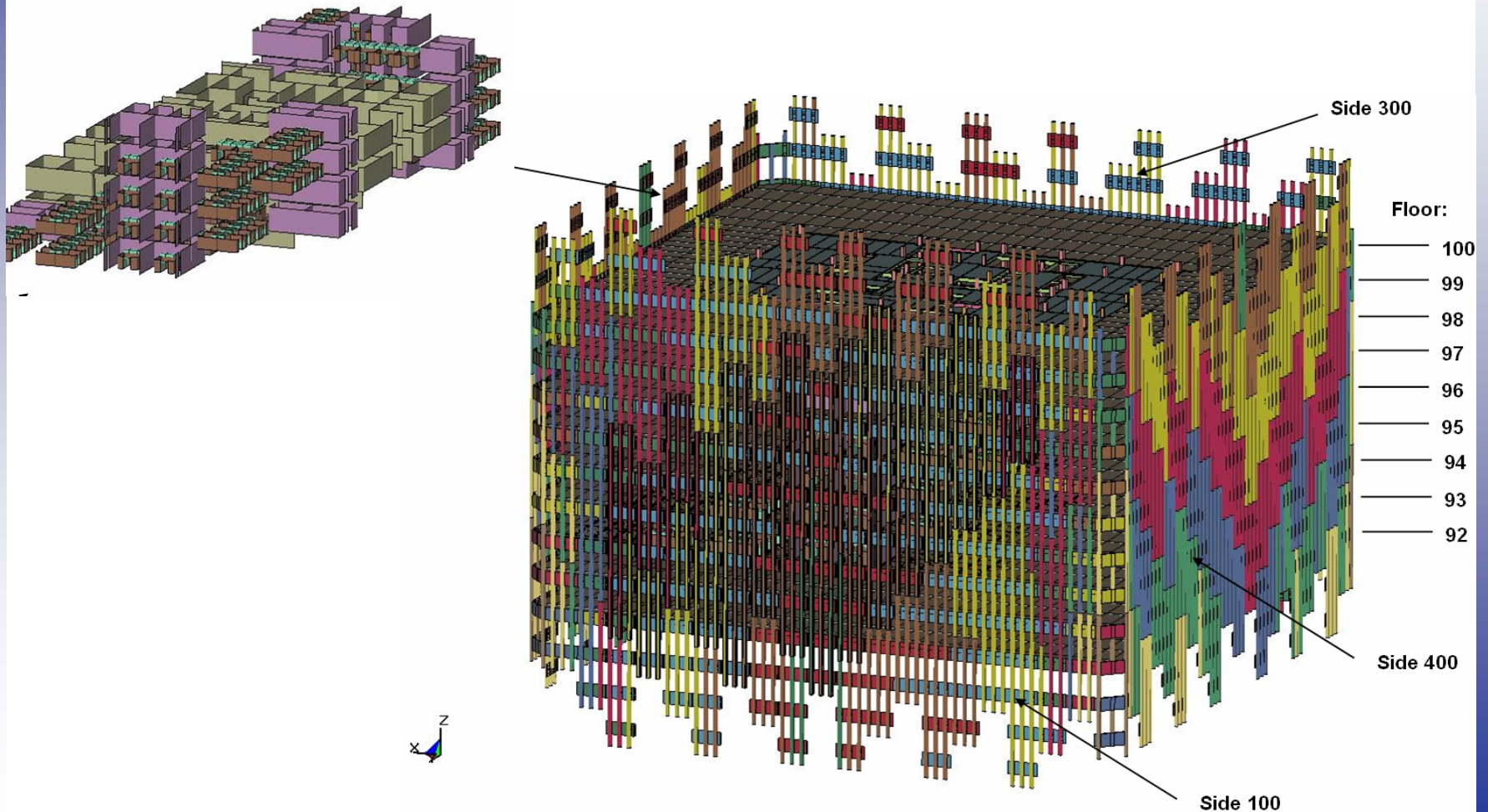
Trading Floor

Source: Reproduced with permission of The Port Authority of New York and New Jersey.

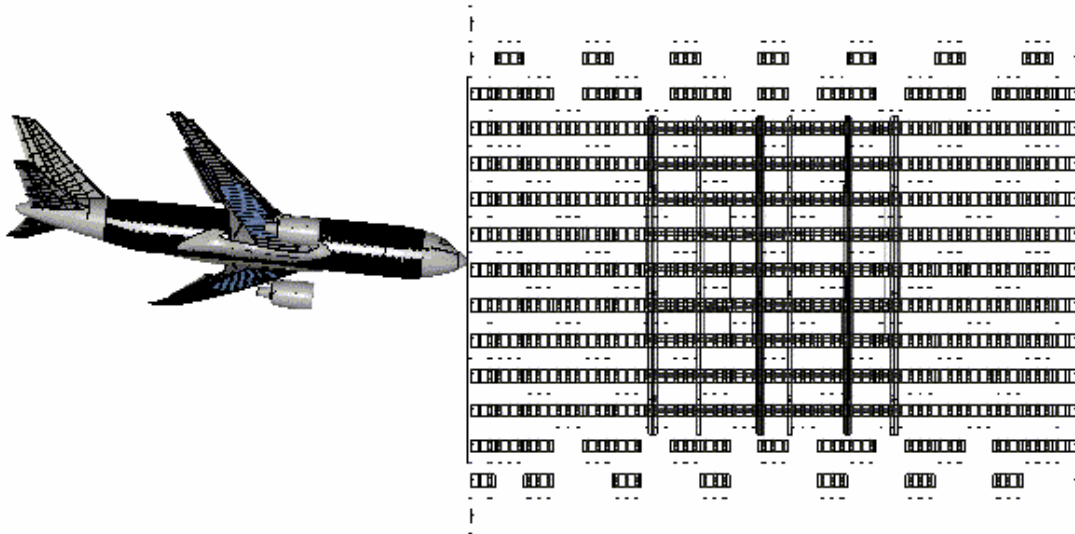
Map of steel obtained by NIST from WTC 1



WTC 1 Tower Model for Aircraft Impact Analysis



Time = 0



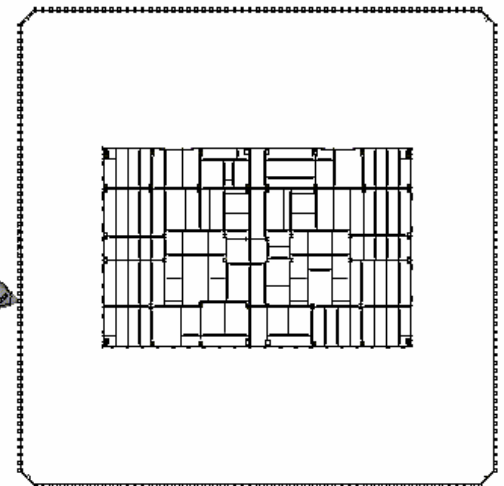
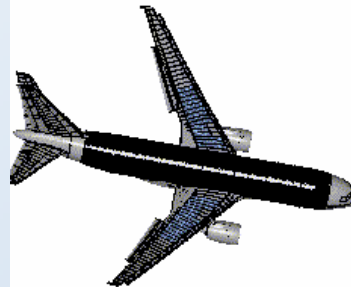
**North Tower (WTC1)
viewed from west**



Time = 0



**South Tower (WTC2)
80th floor**



WTC 1 Damage: Composite Summary for Floors 93 to 98

Severe Floor Damage

Fireproofing and partitions



Floor system structural damage



Floor system removed



Column Damage

Severed



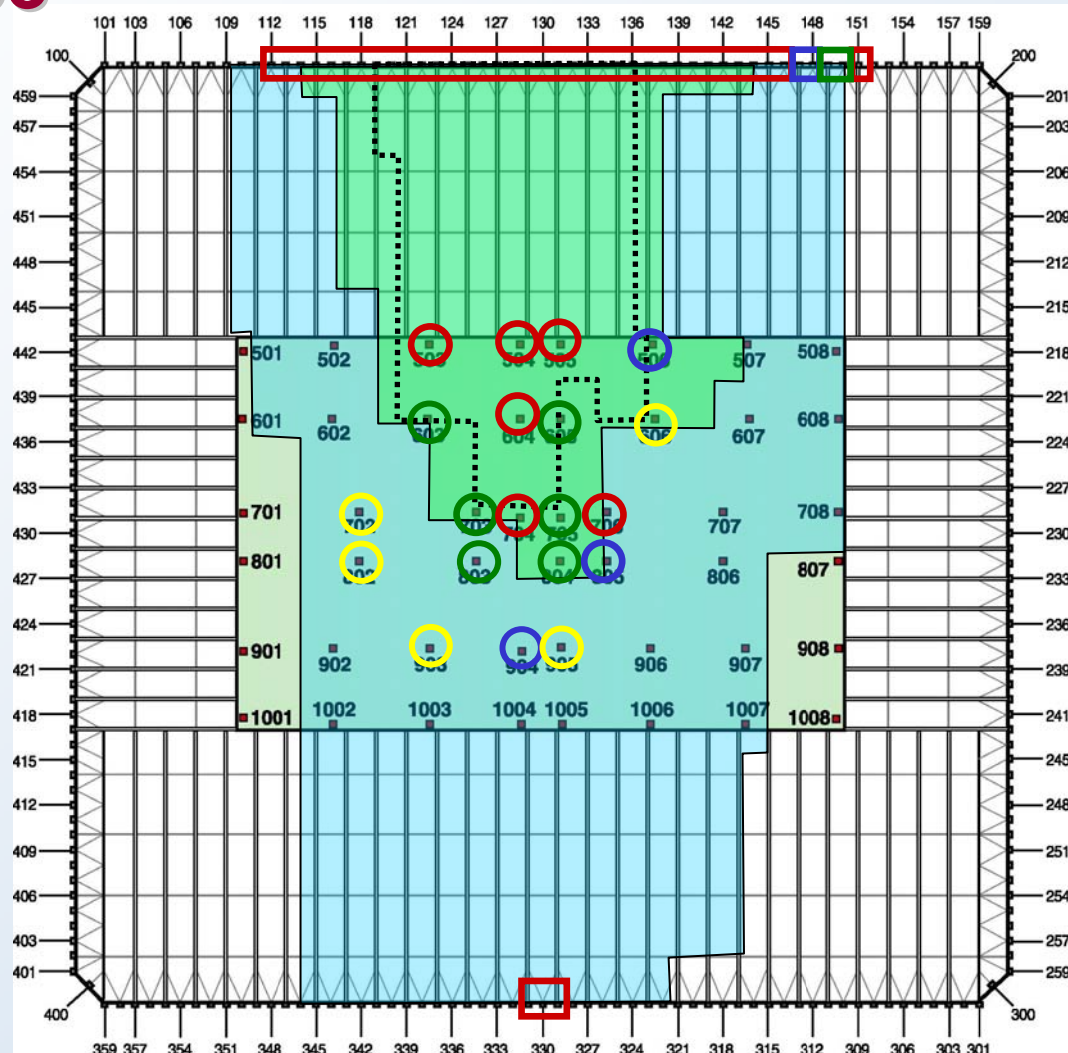
Heavy Damage



Moderate Damage



Light Damage



WTC 2 Damage: Composite Summary for Floors 78 to 83

Floor Damage

Fireproofing and partitions



Floor system structural damage



Floor system removed



Column Damage

Severed



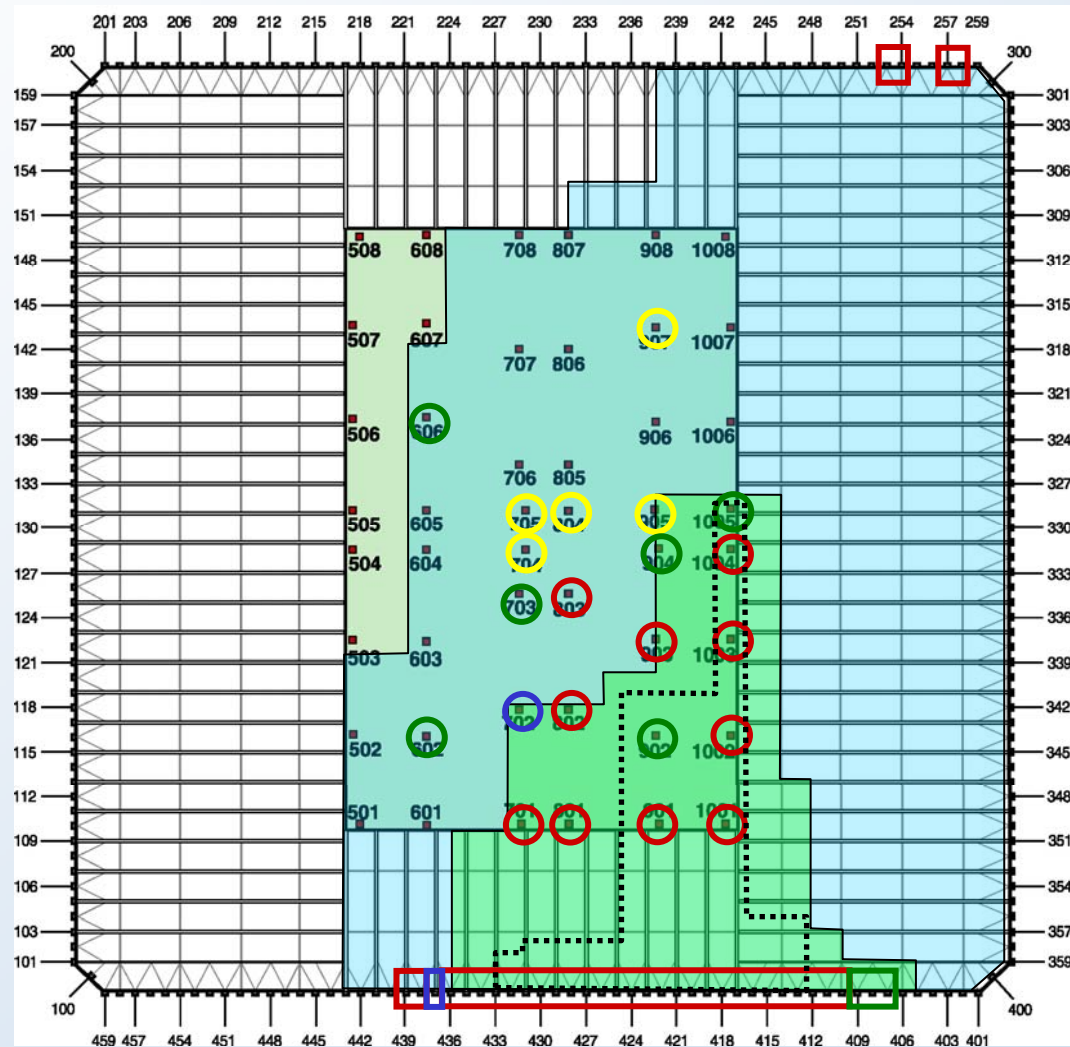
Heavy Damage



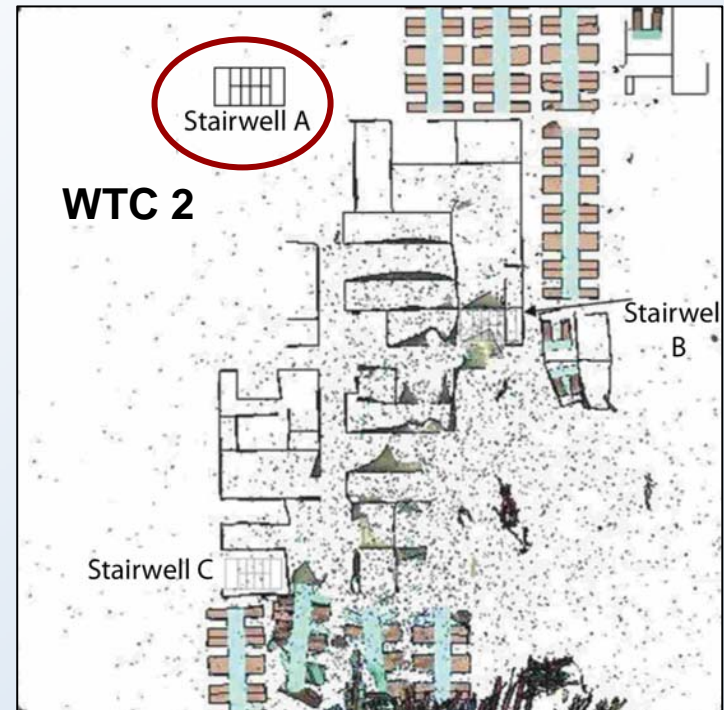
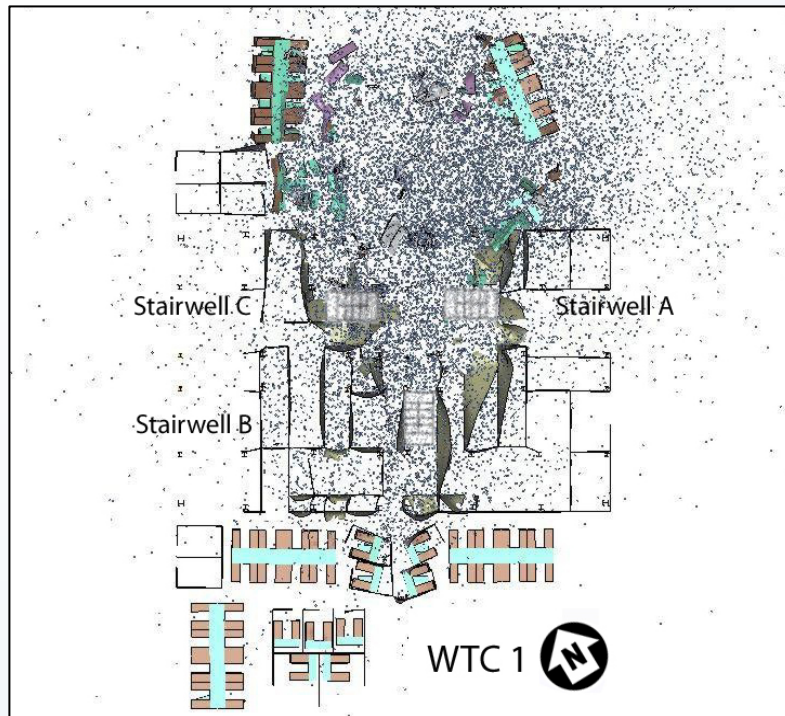
Moderate Damage



Light Damage



Condition of Stairwells



- Stairwells, with partition wall enclosures that provided 2 h fire-rating but little structural integrity, were damaged in region of aircraft impacted floors.
- **Stairwell A on the Northwest side of WTC 2 was passable in region of aircraft impact for some period of time after attack.**
- All three stairwells in WTC 1 and the two other stairwells in WTC 2 were rendered impassable in the region of aircraft impact.

Collection and Analysis of Photographic and Video Images

Visual database contains:

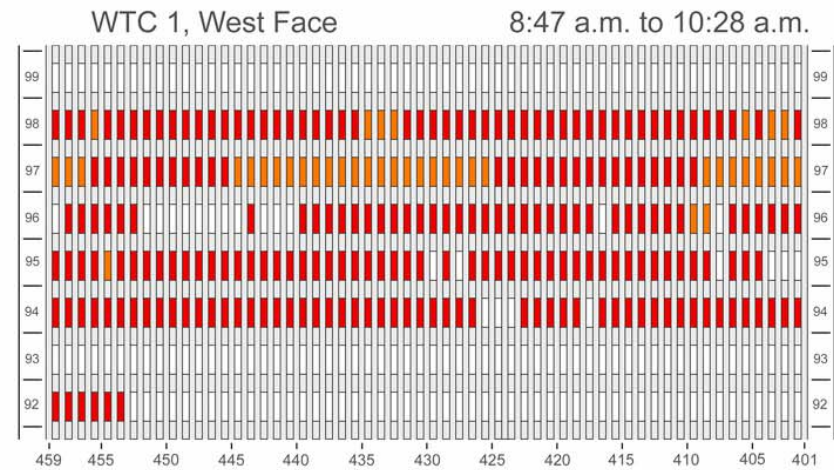
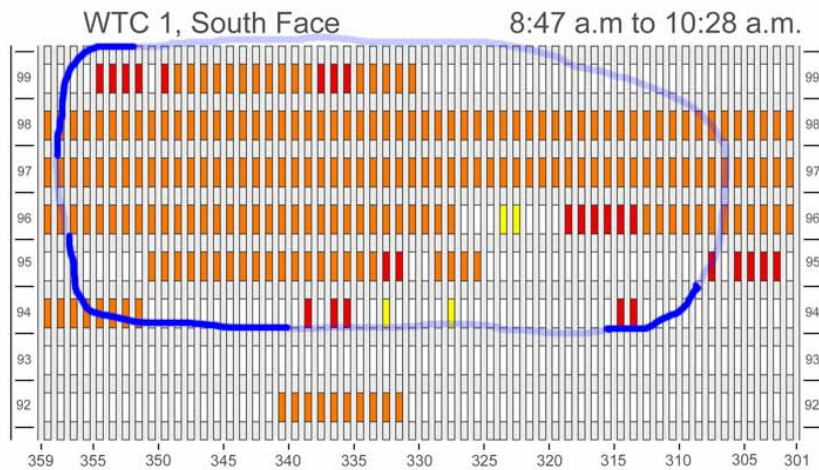
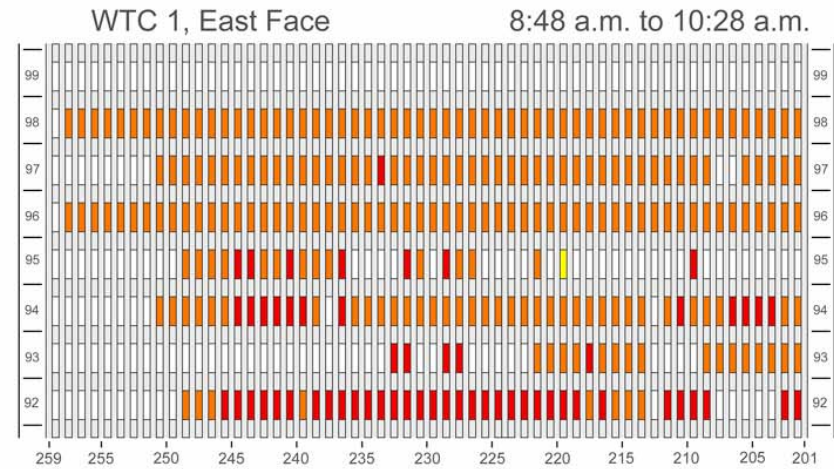
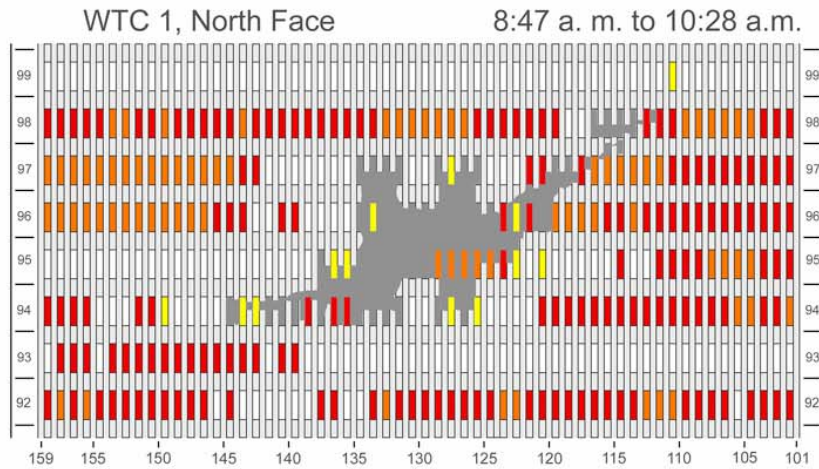
- ❑ Well in excess of 7,000 photographs taken by more than 185 photographers
- ❑ 150 hours of videotape from major media outlets, more than 20 individuals

From analysis of images, NIST has identified significant events for WTC 1 and 2 related to aircraft impact, fire development, and building damage

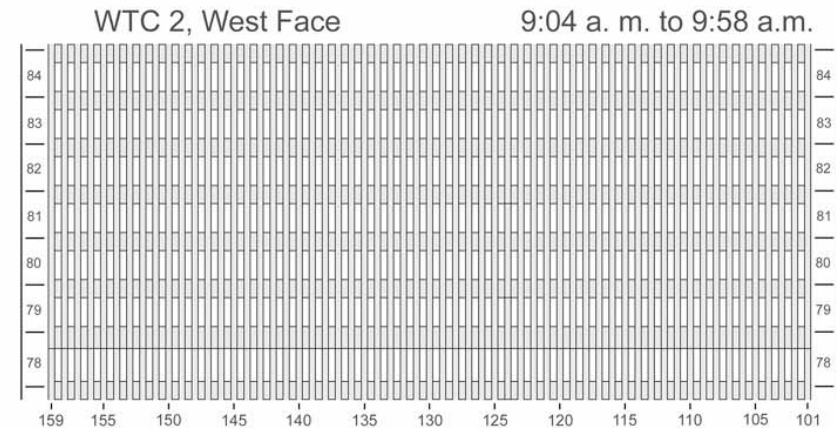
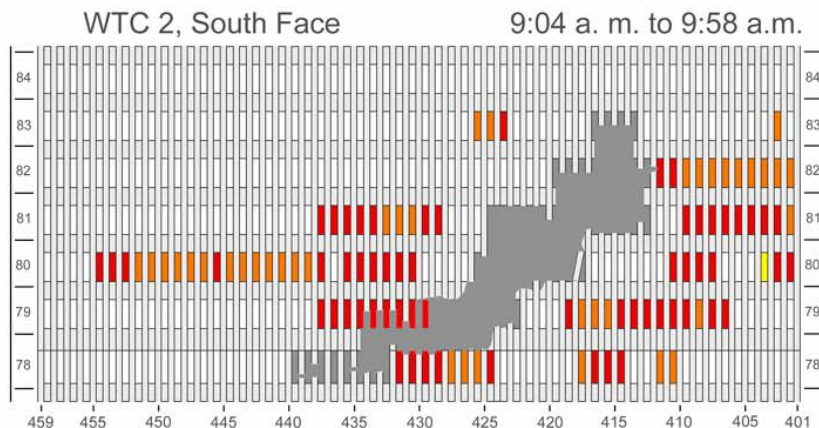
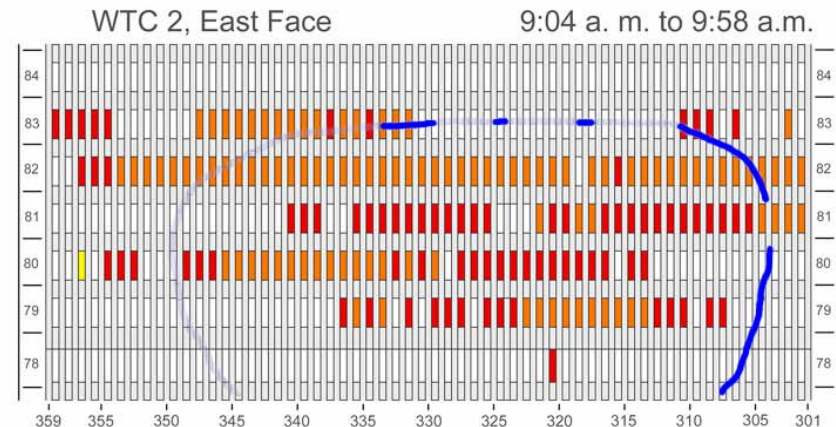
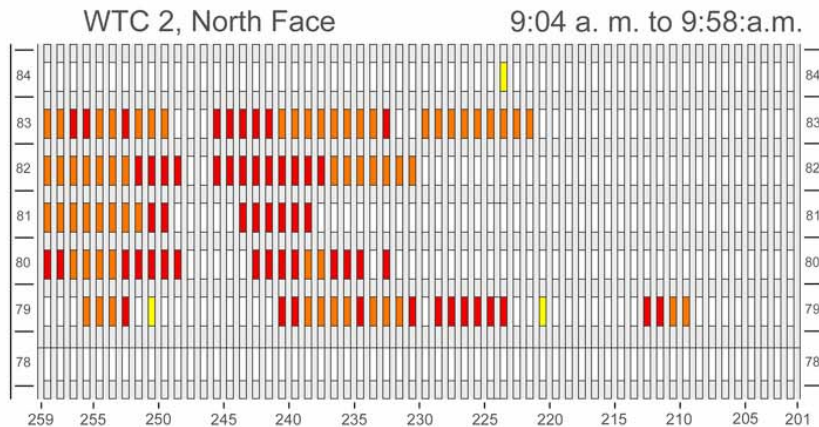
NIST has developed detailed mappings for fire, smoke, and condition of windows at several specific times for each tower.



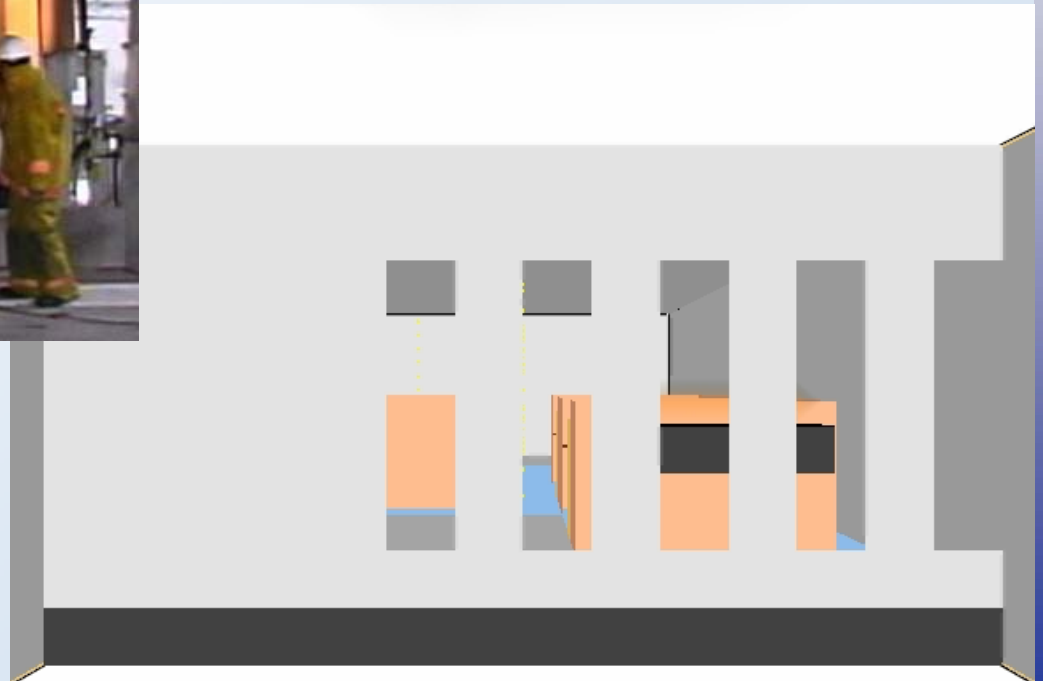
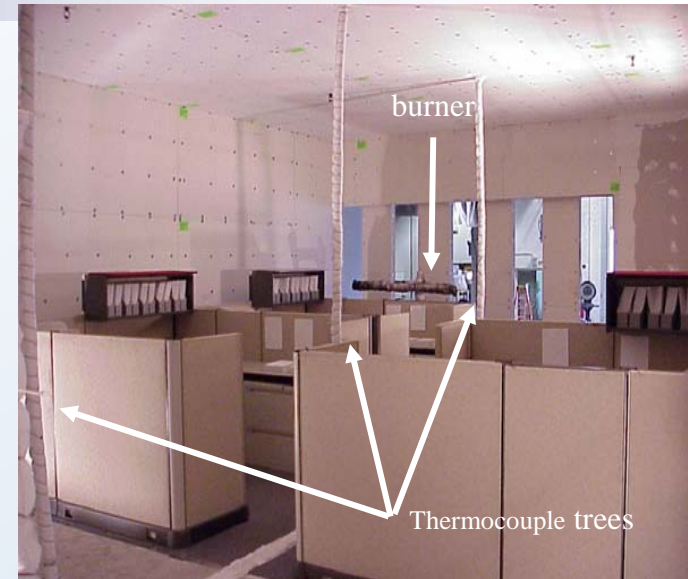
Visual Evidence of Fires in WTC 1



Visual Evidence of Fires in WTC 2

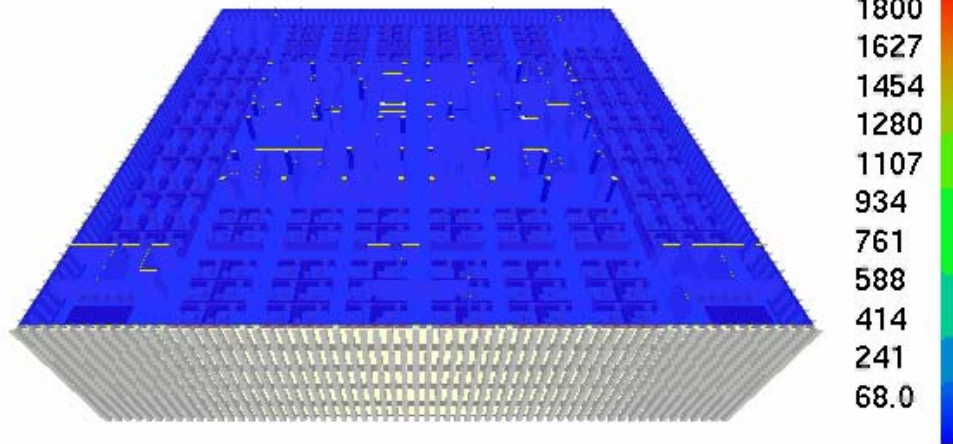


Testing Conducted to Support Computer Simulation of Fires

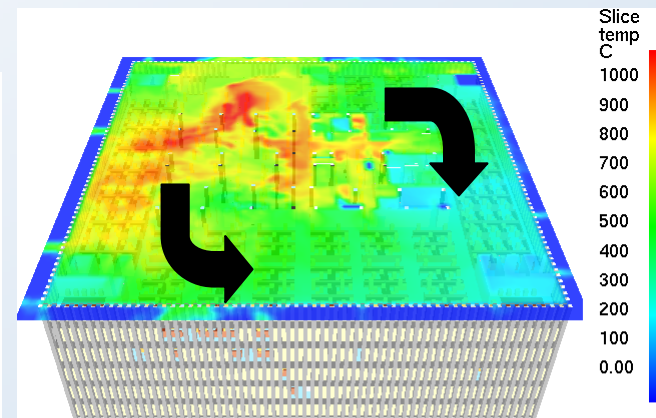


Fire Dynamic Simulator (FDS) Prediction of Upper Layer Temperatures (WTC 1, Floor 97)

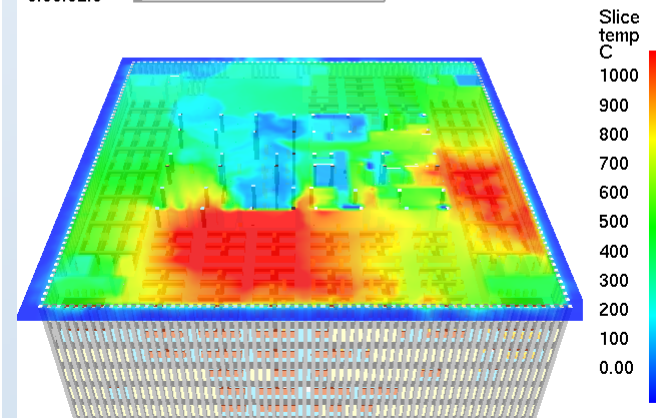
NIST



0:00:00.0



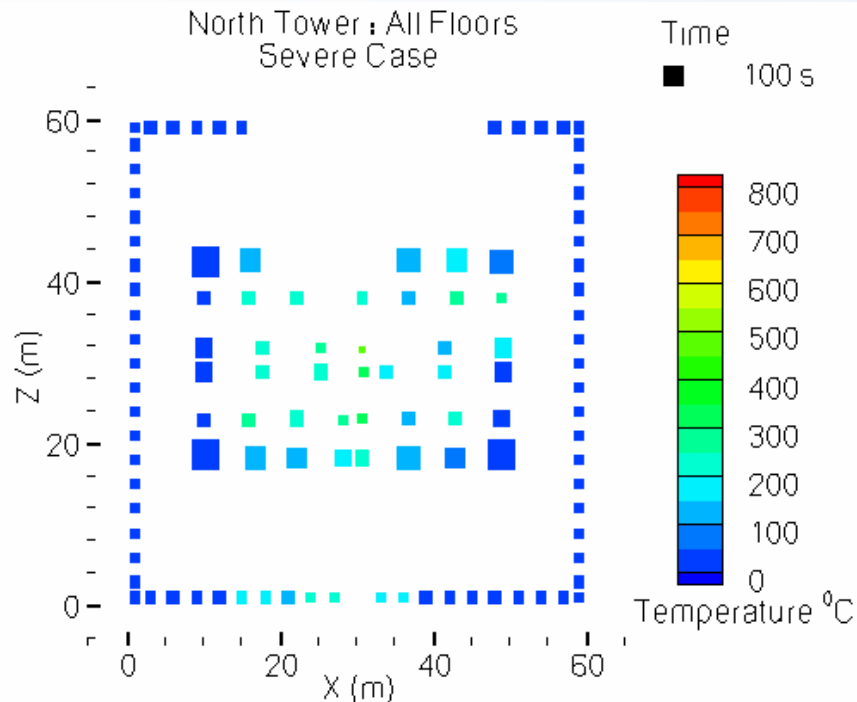
0:03:32.0



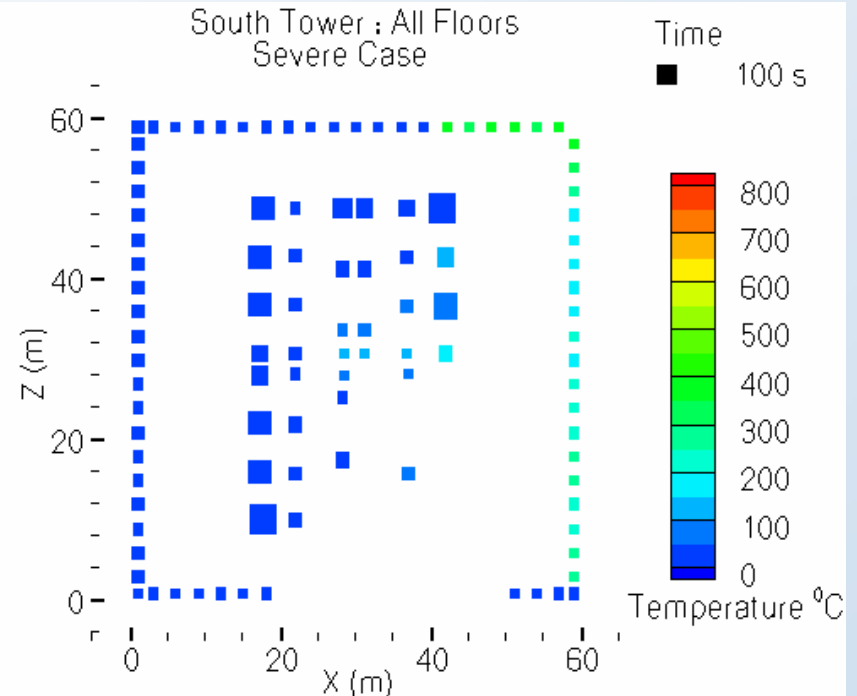
1:40:00.0

Predicted Column Temperatures

WTC 1



WTC 2



Shows maximum temperature reached by each column.

Relative Roles of Aircraft Impact and Fires

Aircraft impact damage did not, by itself, initiate building collapse; it contributed greatly to subsequent fires and thermal response of structures by:

- ❑ Compromising sprinkler and water supply systems;
- ❑ Dispersing jet fuel and igniting building contents over large areas;
- ❑ Creating large accumulations of combustible matter containing aircraft debris and building contents;
- ❑ Increasing air supply into damaged buildings that permitted significantly higher energy release rates than would normally be seen in ventilation limited building fires, allowing fires to spread rapidly on multiple floors;
- ❑ Damaging/dislodging fireproofing from structural components in direct path of debris and due to strong vibrations generated by aircraft impact; and
- ❑ Damaging ceilings that enabled “unabated” heat transport over floor-to-ceiling partition walls and to structural components.

Relative Roles of Aircraft Impact and Fires (2)

The jet fuel was mostly consumed within first minutes after impact. Fires that burned for almost entire time that buildings remained standing were due mainly to burning building contents and, to lesser extent, aircraft contents.

Typical office furnishings were able to sustain intense fires for at least an hour on a given floor. No structural component, however, was subject to intense fires for entire period of burning. Duration of intense burning impacting any specific component was controlled by:

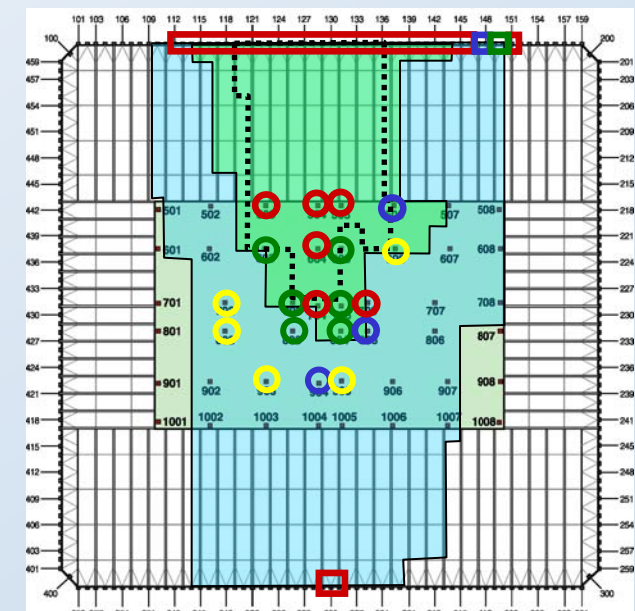
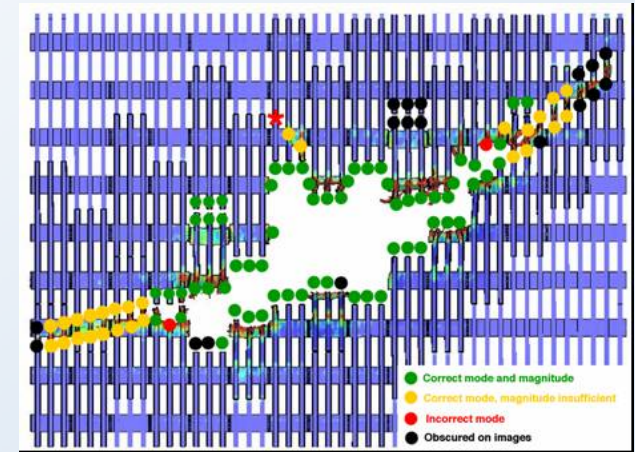
- ☐ Availability of combustible materials
- ☐ Fuel gases released by those combustibles
- ☐ Combustion air in specific area

Typical floor had on average about 4 psf of combustible materials on floors. Mass of aircraft solid combustibles was significant in immediate impact region of both WTC towers.

WTC 1 Probable Collapse Sequence

Aircraft Impact Damage

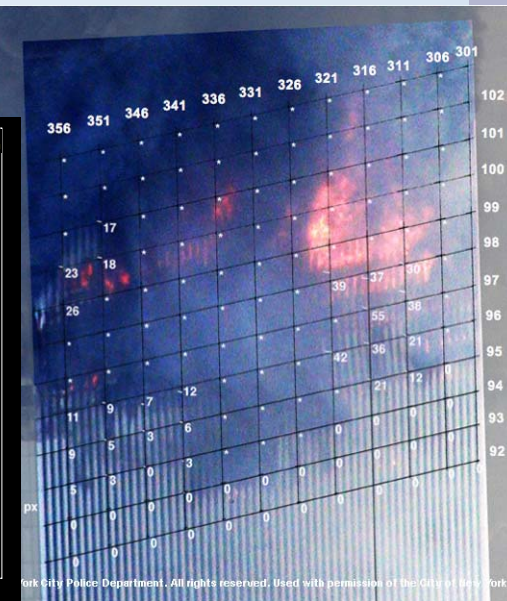
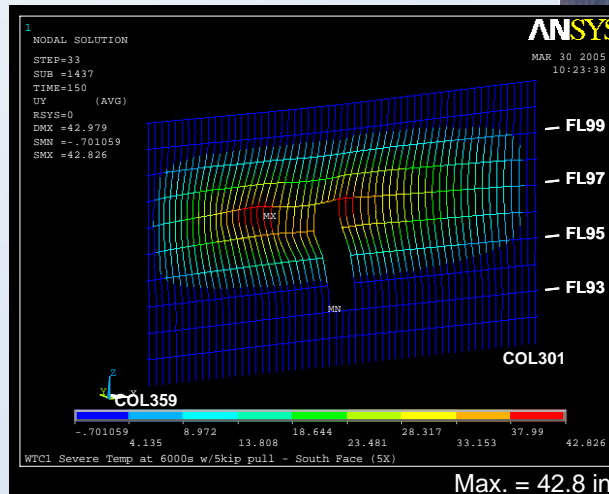
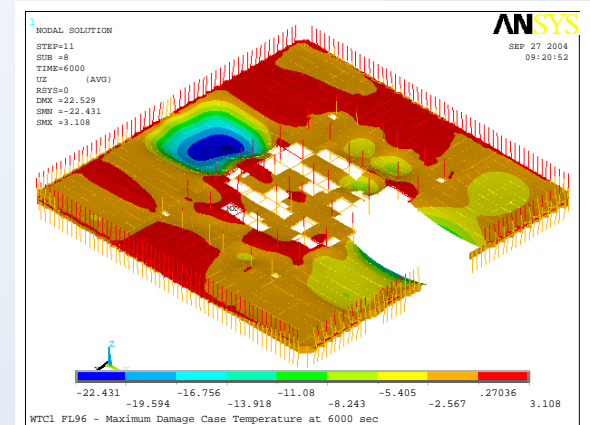
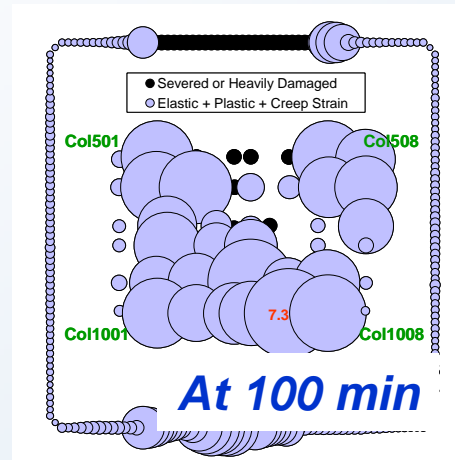
- ❑ Exterior columns, floor sections, and core columns were severed through the building center. An exterior panel was severed at the south wall.
- ❑ Fire protection was damaged through the building center to the south exterior wall.
- ❑ Loads were redistributed mostly to adjacent columns and the hat truss resisted downward movement of the north wall.
- ❑ North and south walls carried 7% less load, east and west wall carried 7% more load, core carried 1% more load.



WTC 1 Probable Collapse Sequence (cont.)

Thermal Weakening

- ❑ Core columns developed high plastic and creep strains, after initial thermal expansion. Hat truss resisted core column shortening.
- ❑ Long span south floors sagged and pulled inward on the south exterior wall after the fires reached the south side.
- ❑ The south wall bowed inward due to inward pull by intact sagging floors.



WTC 1 Probable Collapse Sequence (cont.)

Collapse Initiation

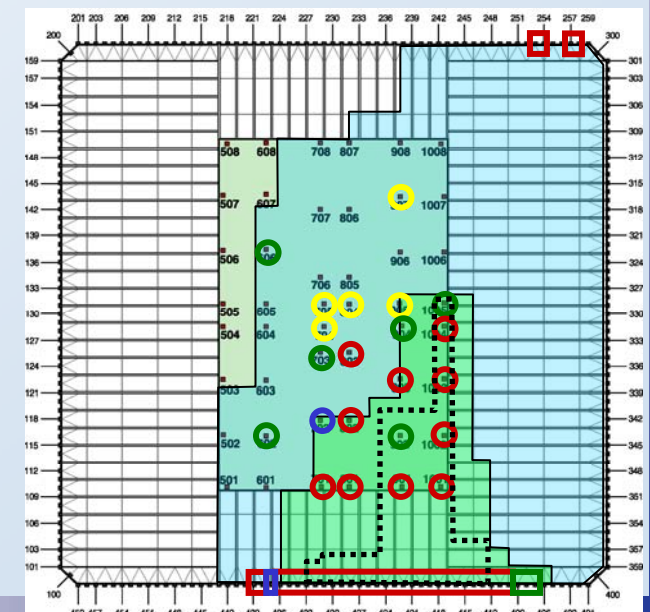
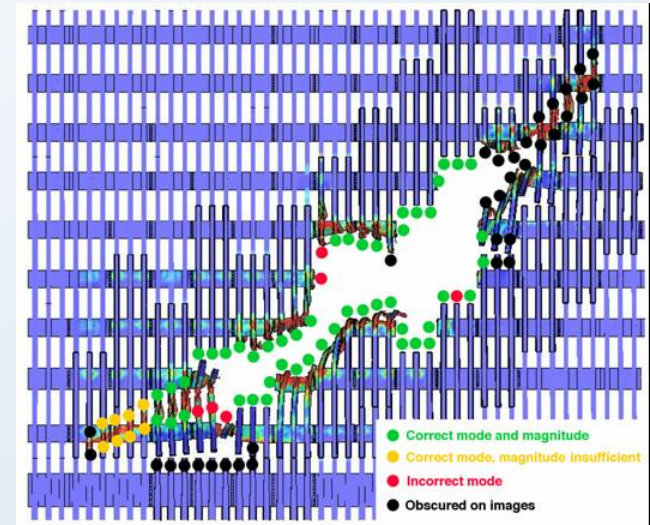
- ❑ The south wall buckled and transferred its loads to the weakened core through the hat truss and to the adjacent exterior walls through the spandrels.
- ❑ The upper building sections began to tilt to the south as a rigid block.
- ❑ Instability progressed along the east and west exterior walls.
- ❑ Collapse ensued as the released potential energy could not be resisted by the structure.



WTC 2 Probable Collapse Sequence

Aircraft Impact Damage

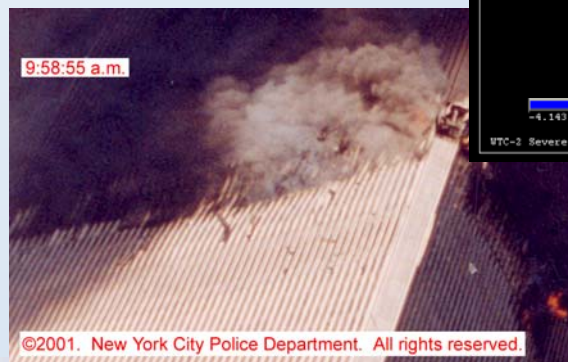
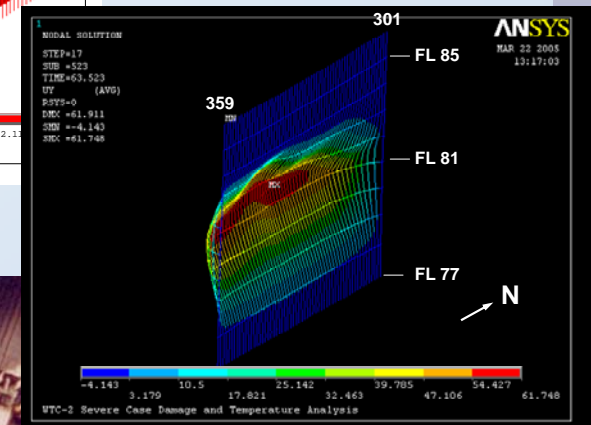
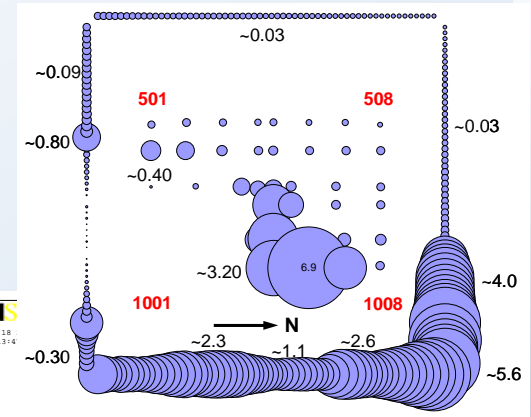
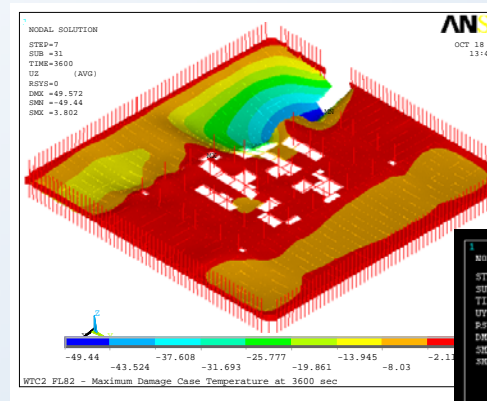
- ❑ Exterior columns, floor sections, and core columns were severed through the southeast corner and east side of the building.
- ❑ Loads were redistributed mostly to adjacent columns and the east exterior wall.
- ❑ Fire protection was damaged in the east side of the building.
- ❑ After impact, the core was leaning slightly toward the east and south walls. The exterior walls restrained the tendency of the core to lean through the hat truss and intact floors.
- ❑ East wall carried 24% more load, south and west wall carried 2-3% more load, north wall carried 10% less load, and the core carried 6% less load.



WTC 2 Probable Collapse Sequence (cont.)

Thermal Weakening

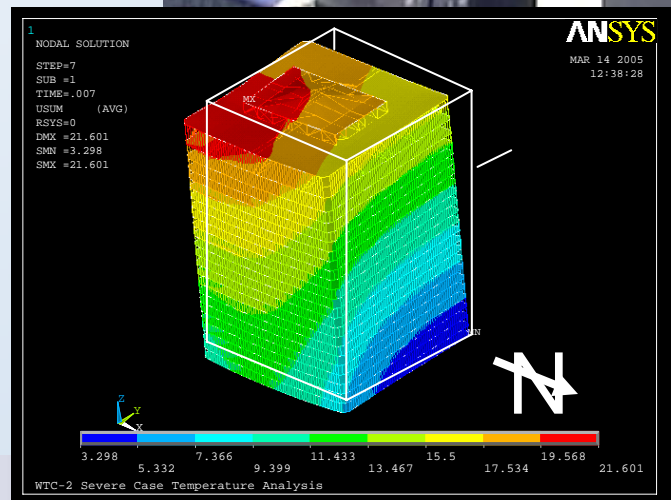
- ❑ Several core columns on the east side developed high plastic and creep strains, after initial thermal expansion.
- ❑ The long-span east floors sagged and pulled inward on the east exterior wall shortly after impact, due to the damage and fires on the east side.
- ❑ About 1/3 of the remaining Floor 83 connections to the exterior wall failed.
- ❑ The east wall bowed inward due to inward pull by intact sagging floors.



WTC 2 Probable Collapse Sequence (cont.)

Collapse Initiation

- ❑ The east wall buckled and transferred its loads to the weakened core through the hat truss and to the adjacent exterior walls through the spandrels.
- ❑ The upper building sections began to tilt to the east and south as a rigid block.
- ❑ Instability progressed along the north and south exterior walls.
- ❑ Collapse ensued as the released potential energy could not be resisted by the structure.



Additional Findings

Role of Thermal Insulation

- ❑ In the absence of structural and thermal insulation damage, a conventional fire substantially similar to or less intense than the fires encountered on September 11, 2001 likely would not have led to the collapse of a WTC tower.

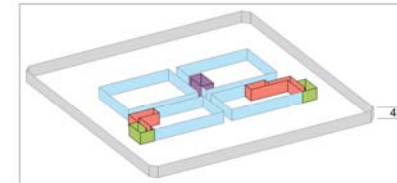
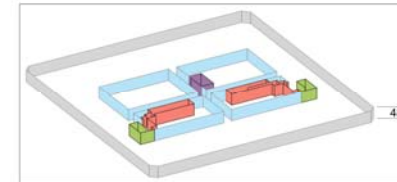
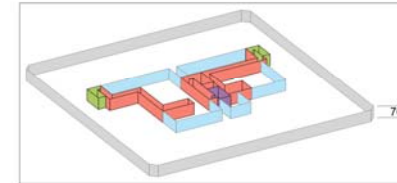
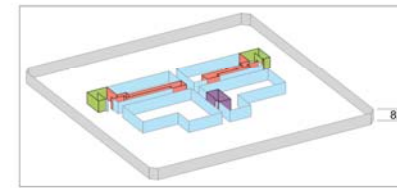
Alternative Hypotheses

- ❑ NIST found no corroborating evidence for alternative hypotheses suggesting that the WTC towers were brought down by controlled demolition using explosives planted prior to September 11, 2001. NIST also did not find any evidence that missiles were fired at or hit the towers. Instead, photos and videos from several angles clearly showed that the collapse initiated at the fire and impact floors and that the collapse progressed from the initiating floors downward, until the dust clouds obscured the view.

Additional Findings (2)

Evacuation Process

- ❑ Under full occupant and visitor loads (19,800 in each tower) and with no delays, models indicate evacuation would have taken close to 2 hours (compared to ~ 3 hours based upon observed egress rate on Sept. 11).
- ❑ In Tower 2, 7700 people would have been trapped above the impact floors.
- ❑ 14,577 people would still have been in the towers when they collapsed.



Stairwell C

Stairwell B

Stairwell A



Additional Findings (3)

Emergency Operations - Situation Awareness

Outside Command Posts;
Inside Command Communicating with
Outside Command Posts:

- ☐ Fires in buildings were too large, located too high, to accomplish fire fighting activities that could save lives of occupants above the fires.
- ☐ **Objective: evacuate and rescue all below the fires.**

Command Officers for Inside Operations:

- ☐ Fires were too large to extinguish.
- ☐ **Objective: get enough personnel and equipment upstairs to cut path through fire to rescue occupants above, and also evacuate and rescue all below fires.**



Additional Findings (4)

Emergency Operations - situation awareness

Company Level Command:

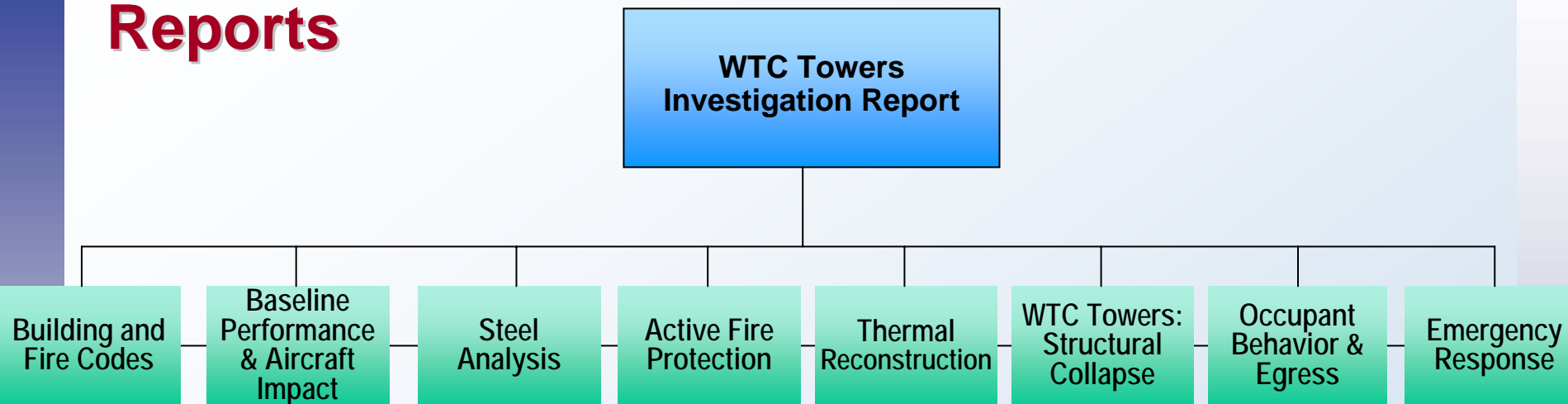
- ☐ Conventional but large high-rise fire.
- ☐ **Objective: get up to fire floors and extinguish fires.**

In some cases, firefighters were persuaded by higher ranking officers to switch from fire fighting to evacuation and rescue operations.

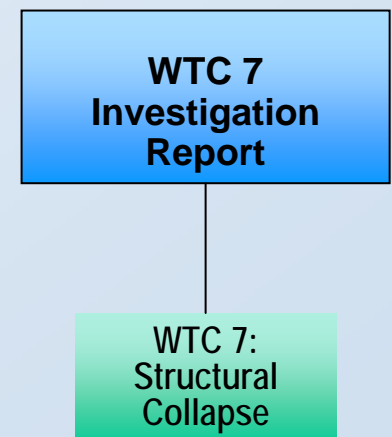
No first responder interviewed by NIST thought that the WTC towers would collapse.



WTC Investigation Reports



- Draft of summary report (NCSTAR 1), 8 draft project reports, and 34 supporting technical reports have been released.
- Public comments collected through August 4, 2005.
- Technical Conference held Sept. 13-15, 2005.
- Draft WTC 7 report to be issued later as supplement to main report.



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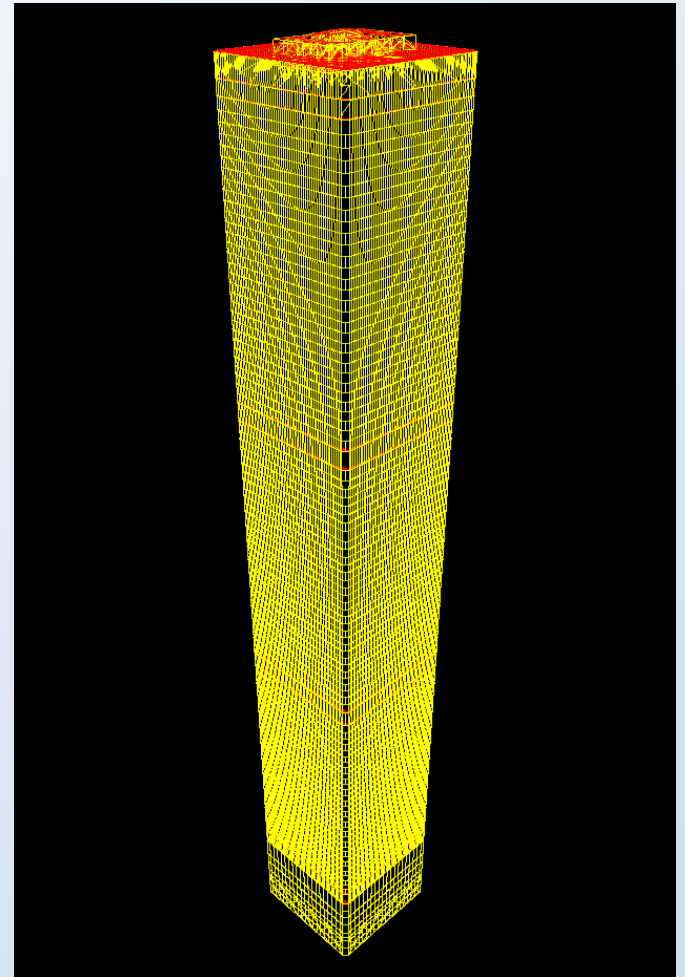
Recommendations

(30 total, in eight groupings)

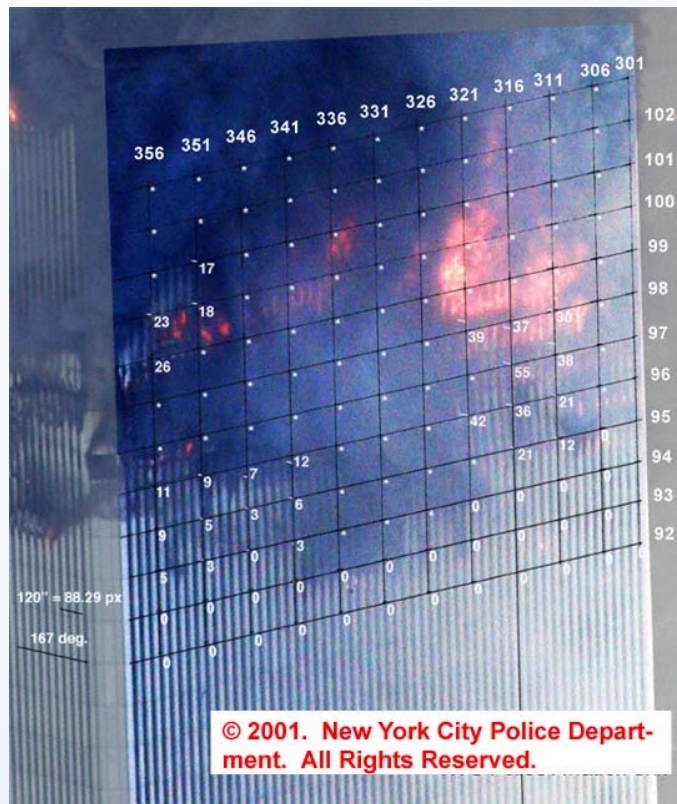
Group 1: Increased Structural Integrity

The standards for estimating the load effects of potential hazards (e.g., progressive collapse, wind) -- and the design of structural systems to mitigate the effects of those hazards -- should be improved to enhance structural integrity.

(Recommendations #1 - #3)



Group 2: Enhanced Fire Resistance of Structures



Procedures and practices used to ensure fire resistance of structures should be enhanced by:

- improving technical basis for construction classifications and fire resistance ratings and testing methods,
- using “structural frame” approach to fire resistance ratings, and
- developing in-service performance requirements and conformance criteria for spray-applied fire resistive materials.

(Recommendations #4 - #7)

Group 3: New Methods for Fire Resistance Design of Structures

Procedures and practices used in fire resistance design of structures should be enhanced by requiring an objective that *uncontrolled fires result in burnout without local or global collapse*. Performance-based methods are an alternative to prescriptive design methods.

This effort should include development and evaluation of:

- new fire resistive coating materials and technologies and
- evaluation of fire performance of conventional and high-performance structural materials.

Technical and standards barriers to introduction of new materials and technologies should be eliminated.

(Recommendations #8 - #11)



Group 4: Improved Active Fire Protection

Active fire protection systems (i.e., sprinklers, standpipes/hoses, fire alarms, and smoke management systems) should be enhanced through improvements to:

- Design
- Performance
- Reliability, and
- Redundancy

of such systems.

(Recommendations #12 - #15)



Group 5: Improved Building Evacuation

Design tall buildings to accommodate *timely full building evacuation* of occupants due to building-specific or large-scale emergencies such as widespread power outages, major earthquakes, tornadoes, hurricanes, fires, accidental explosions, and terrorist attack.

- Building size, population, function, and iconic status should be taken into account in designing egress system.
- Stairwell and exit capacity should be adequate to accommodate counterflow due to emergency access by responders. **Rec. #17**

Design egress systems:

- to *maximize remoteness of egress components* (i.e., stairs, elevators, exits) without negatively impacting average travel distance;
- to maintain their functional *integrity and survivability* under foreseeable building-specific or large-scale emergencies; and
- with consistent layouts, standard signage, and guidance so that systems become *intuitive and obvious* to building occupants during evacuations.

Rec. #18

Improved Building Evacuation (2)

Building owners, managers, and emergency responders should develop a joint plan and *ensure accurate emergency information is communicated* in timely manner to enhance awareness of occupants and emergency responders through:

- better coordination of information among different emergency responder groups,
- efficient sharing of that information among building occupants and emergency responders,
- more robust design of emergency public address systems,
- improved emergency responder communication systems, and
- use of the Emergency Broadcast System (Integrated Public Alert and Warning System) and Community Emergency Alert Networks. **Rec. #19**

Group 6: Improved Emergency Response Technologies and Procedures

Install *fire-protected and structurally hardened elevators in tall buildings* to provide timely emergency access to responders and allow evacuation of mobility impaired building occupants.

- Such elevators should be for exclusive use by emergency responders during emergencies.
- In tall buildings, consideration also should be given to installing such elevators for use by all occupants. **Rec. #21**

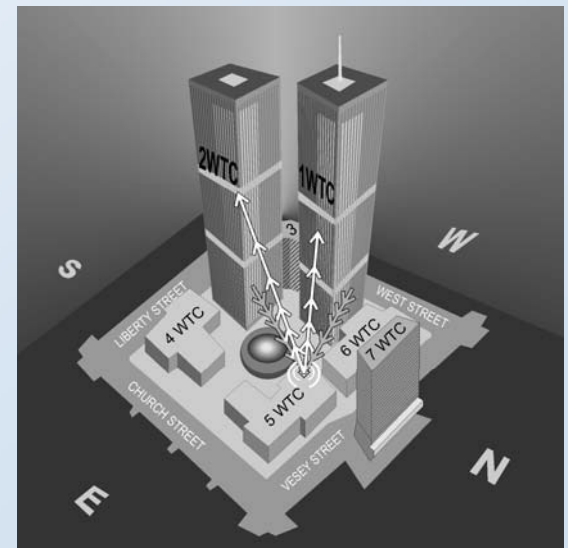
Install, inspect, and test *emergency communications systems, radio communications, and associated operating protocols* to ensure that systems and protocols:

- are effective for large-scale emergencies in buildings with challenging radio frequency propagation environments, and
- can be used to identify, locate, and track emergency responders within indoor building environments and in field. **Rec. #22**

Improved Emergency Response Technologies and Procedures (2)

Establish and implement detailed procedures and methods for gathering, processing, and delivering critical information through *integration of relevant voice, video, graphical, and written data* to enhance situational awareness of all emergency responders. Establish an *information intelligence sector* to coordinate each incident. **Rec. #23**

Establish and implement codes and protocols for ensuring *effective and uninterrupted operation of command and control system* for large-scale building emergencies. **Rec. #24**



Group 7: Improved Procedures and Practices

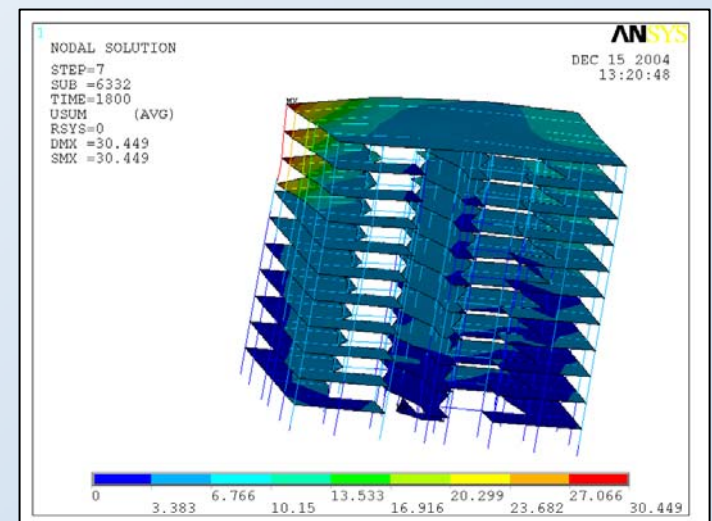
The procedures and practices used in the design, construction, maintenance, and operation of buildings should be improved by:

- encouraging code compliance by nongovernmental and quasi-governmental entities,
- adoption and application of egress and sprinkler requirements in codes for existing buildings, and
- retention and availability of building documents over the life of a building.



Group 8: Education and Training

The skills of building and fire safety professionals should be upgraded through a national education and training effort for fire protection engineers, structural engineers, and architects.



Recommendations: Call to Action

NIST strongly urges the building and fire safety communities to give ***immediate and serious consideration*** to these recommendations in order to achieve appropriate improvements in the way buildings are designed, constructed, maintained, and used and in evacuation and emergency response procedures.

NIST strongly urges building owners and public officials to:

1. evaluate the safety implications of these recommendations to their ***existing inventory of buildings***; and
2. take the steps necessary to mitigate any ***unwarranted risks*** without waiting for changes to occur in codes, standards, and practices.

NIST strongly urges state and local agencies to ***rigorously enforce*** building codes and standards since such enforcement is critical to ensure the expected level of safety.

NIST Actions

After issuance of the final report, the National Construction Safety Team Act requires NIST to:

- Conduct, or enable or encourage the conduct of, appropriate research recommended by the NCST; and
- Promote the appropriate adoption of the recommendations by the Federal Government and other agencies and organizations.

NIST is assigning *top priority* to work vigorously with the building and fire safety communities to assure that there is a complete understanding of the recommendations and to provide needed technical assistance.

Copies of final reports available at <http://wtc.nist.gov>